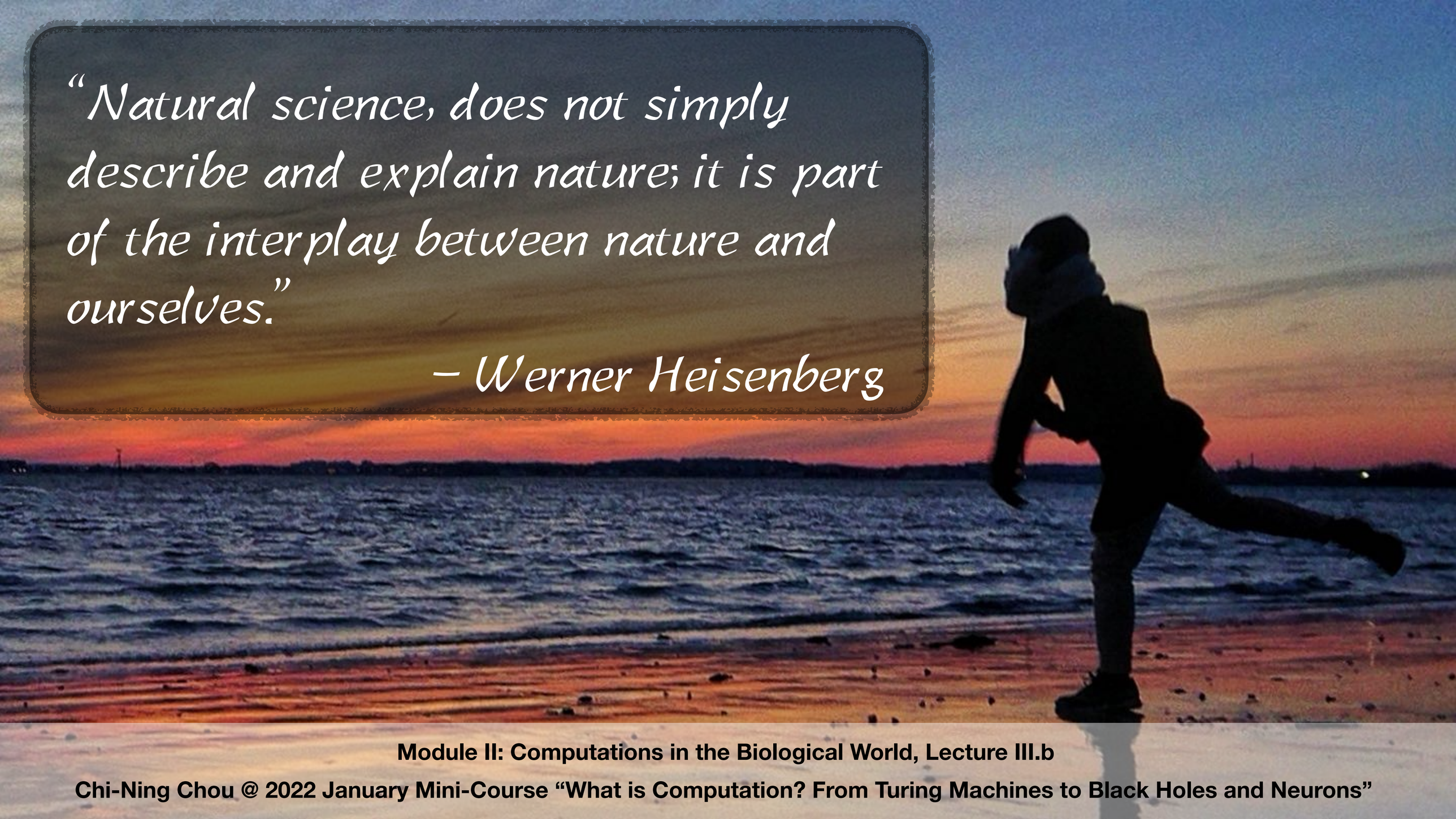


Module II: Computations in the Biological World, Lecture III.b

Chi-Ning Chou @ 2022 January Mini-Course "What is Computation? From Turing Machines to Black Holes and Neurons"

Two Mysteries: Evolution and Neuroscience

Module III: Computations in the Biological World

"Natural science, does not simply describe and explain nature; it is part of the interplay between nature and ourselves."

– Werner Heisenberg

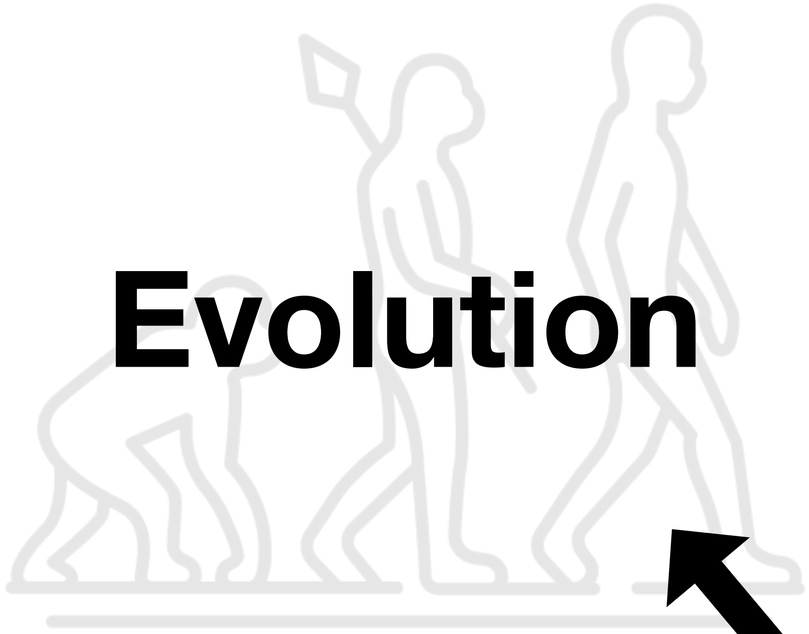
Last Lecture

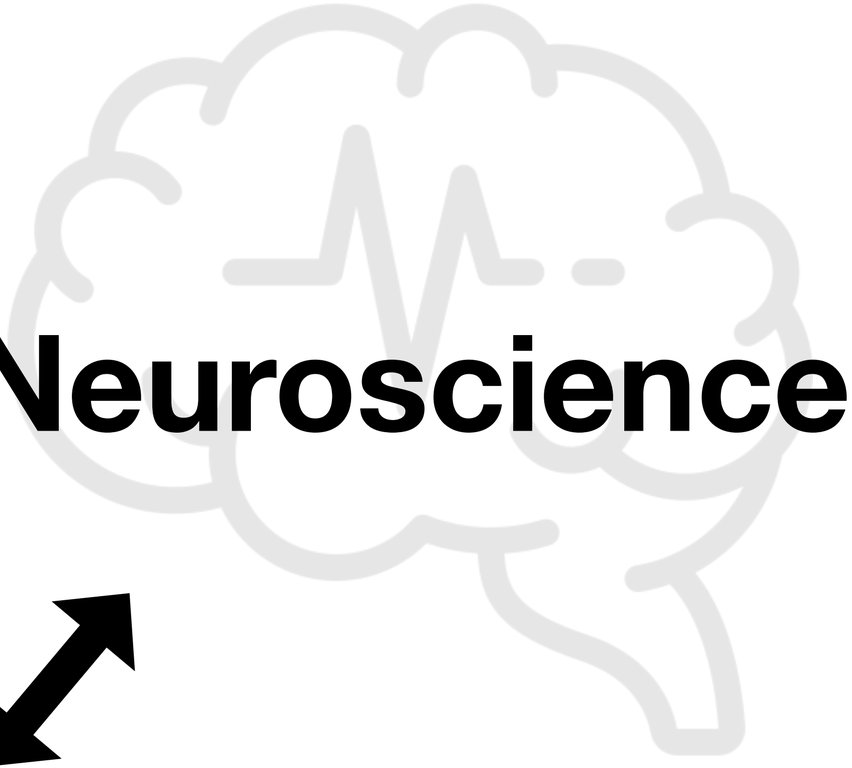
- What is biology?
- Marr’s three levels.
- Computational biology & bioinformatics.
- Biological computations.

- Evolution.
- Neuroscience.

This Lecture

Two Mysteries





Evolution **Neuroscience**

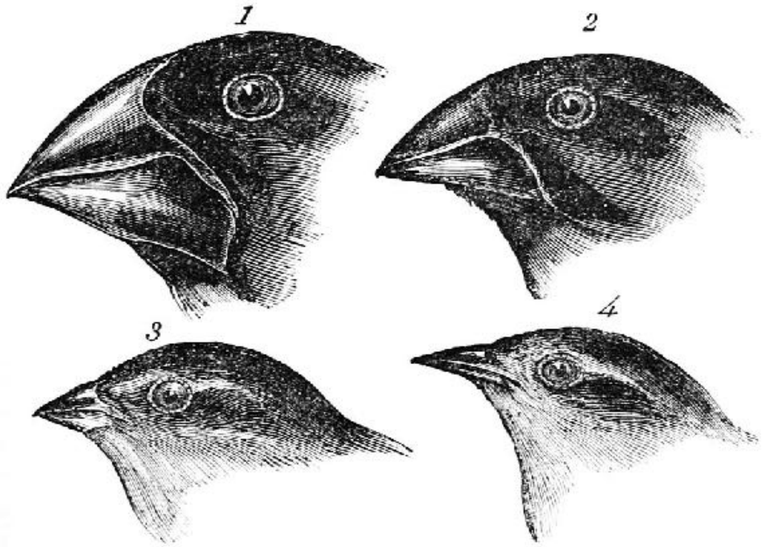
Computation

Evolution

"Evolution has no long-term goal. There is no long-distance target, no final perfection to serve as a criterion for selection."

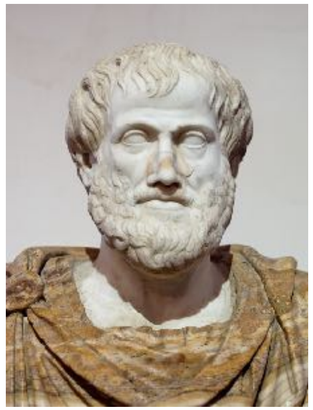
– Richard Dawkins

Structure and Randomness



What's the underlying reason for diversity and similarity?

Before and After Darwin's Journey



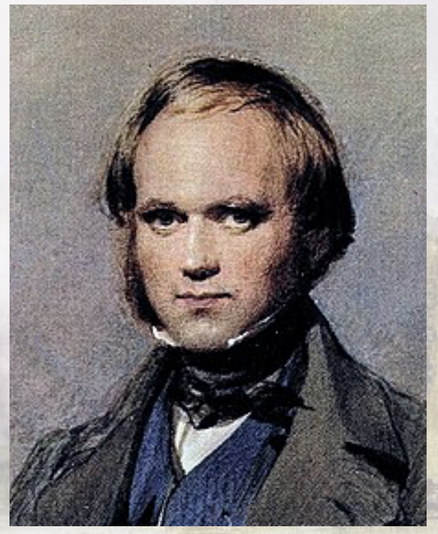
Aristotle
384BC-322BC

"The useful forms survive."

"The acquired characteristics can be inherited."

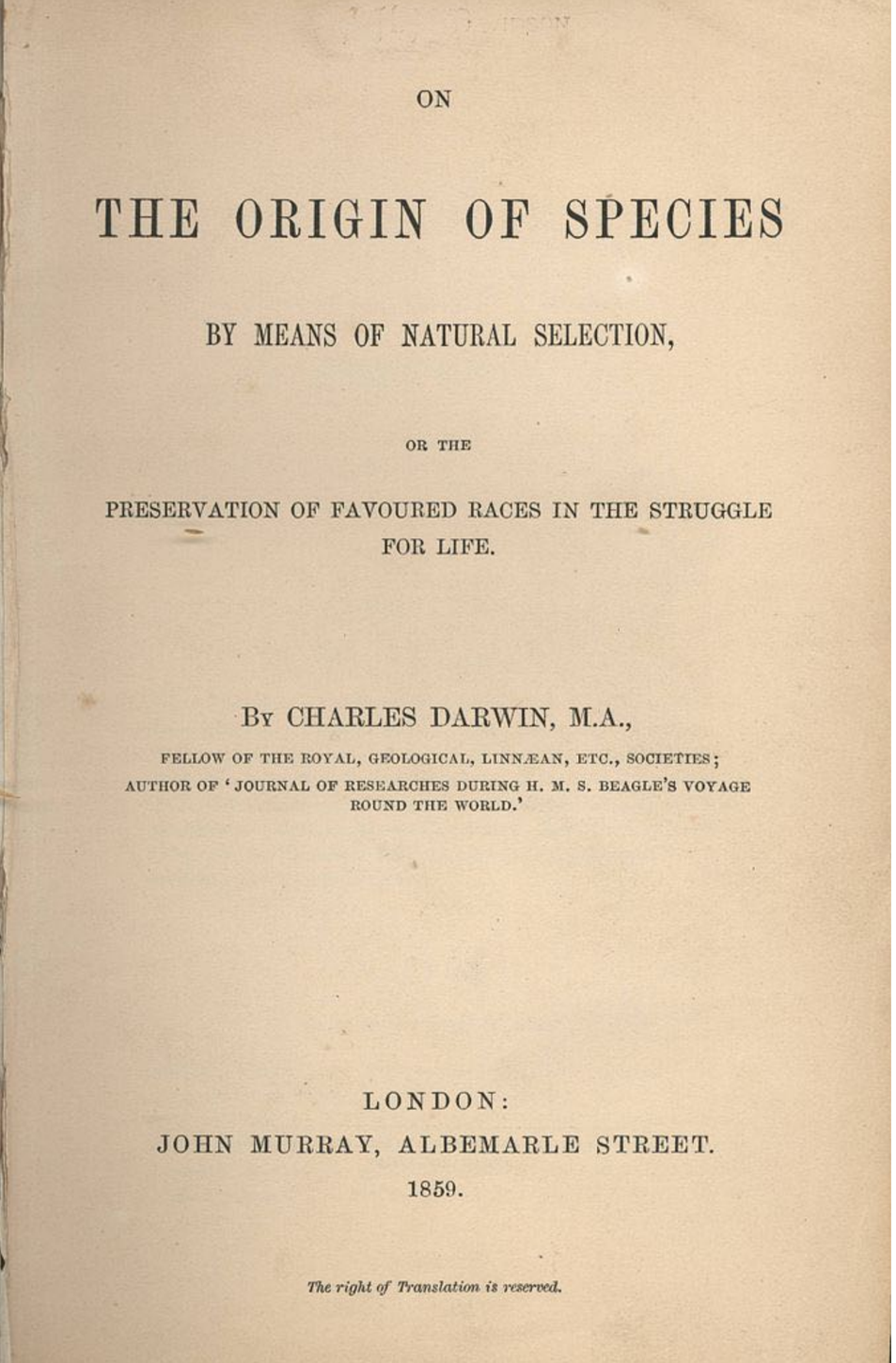
Jean-Baptiste Lamarck
1744-1829

"Natural Selection."



Charles Darwin
1809-1882

The Beagle Expedition
1831-1836



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.

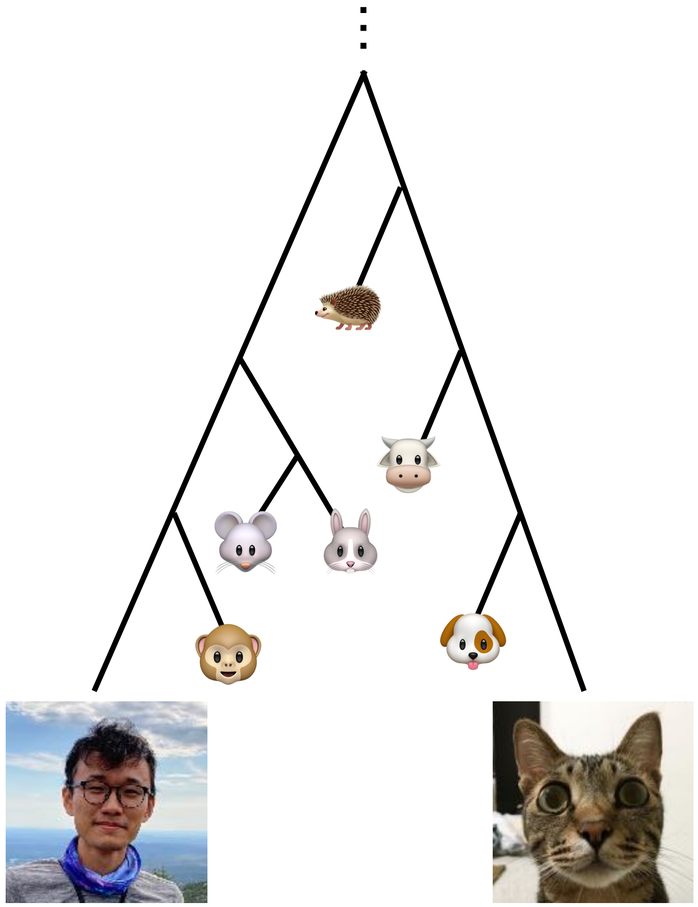
The Origin of Species

By Means of Natural Selection,

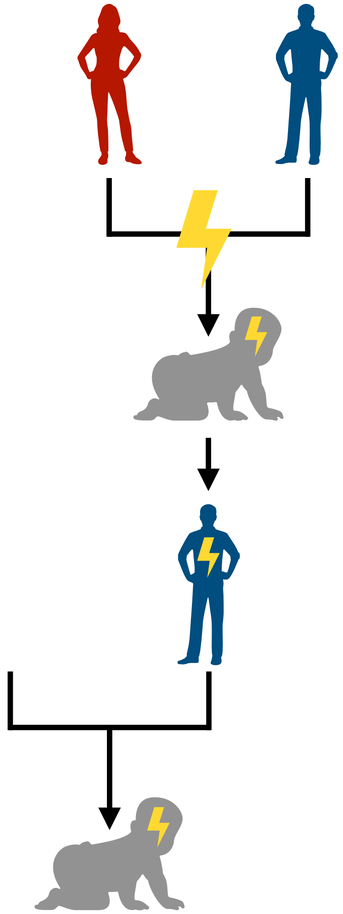
or the

Preservation of Favoured Races in the Struggle for Life.

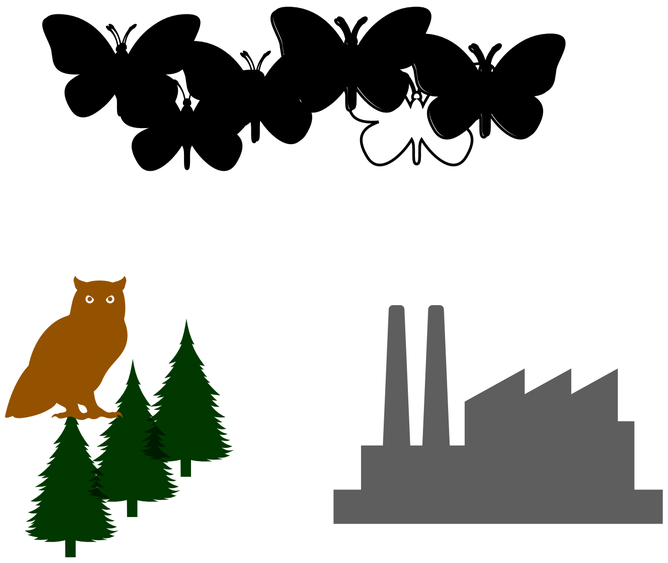
The Essence of Natural Selection



Common descent



Heredity & Variation



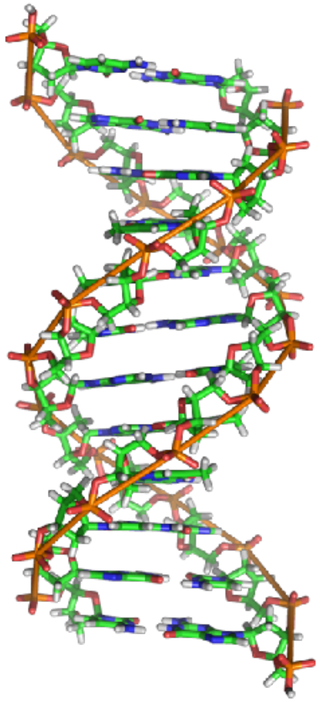
Competition & Fitness

How to “Prove” the Validity of Natural Selection?

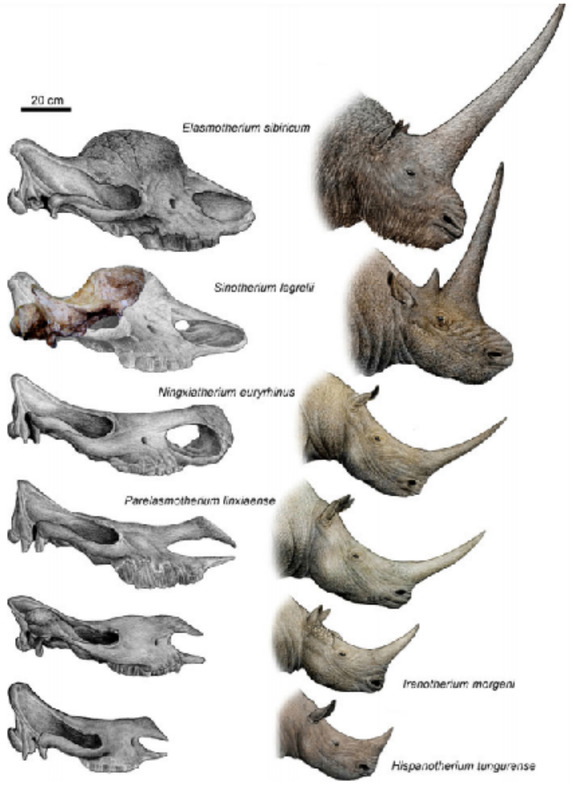
“Well, evolution is a theory. It is also a fact. And facts and theories are different things, not rungs in a hierarchy of increasing certainty. Facts are the world’s data. Theories are structures of ideas that explain and interpret facts.”

– Stephen Jay Gould

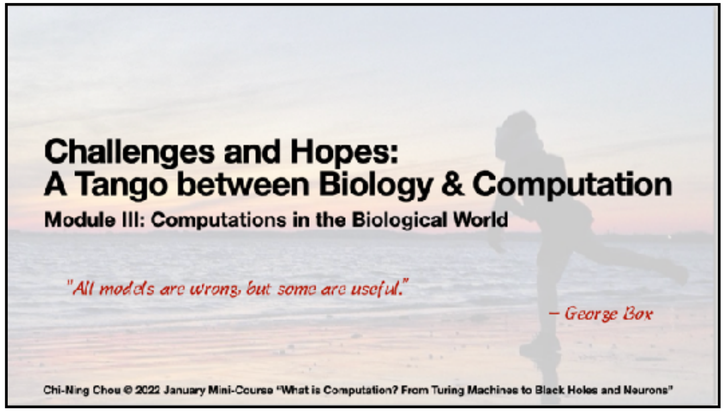
Evidence Supporting Natural Selection



Genetics



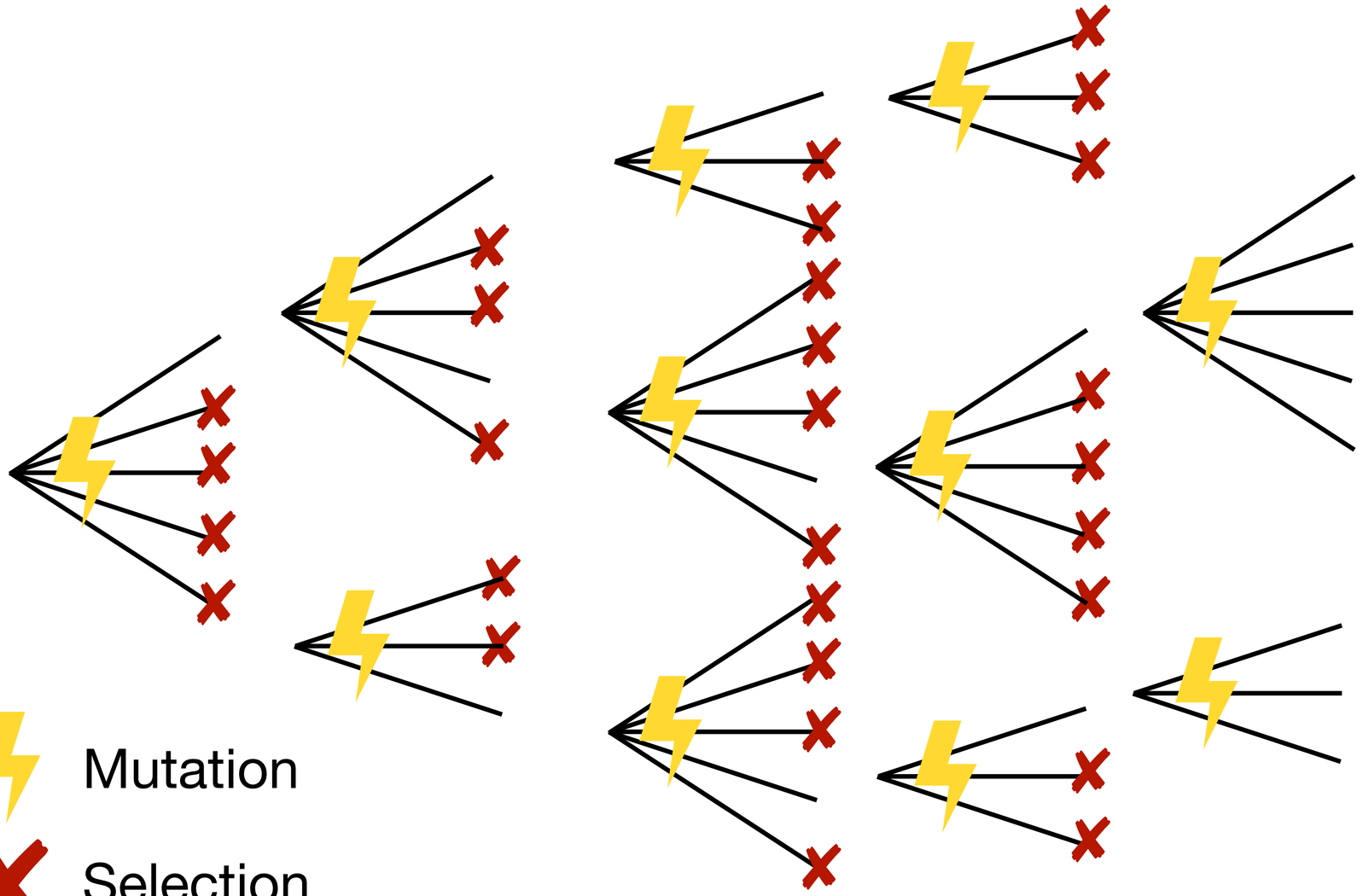
Fossils



Lecture III.c

(Jan. 20 10am-10:50am ET)

A New Angle to See the World



Mutation

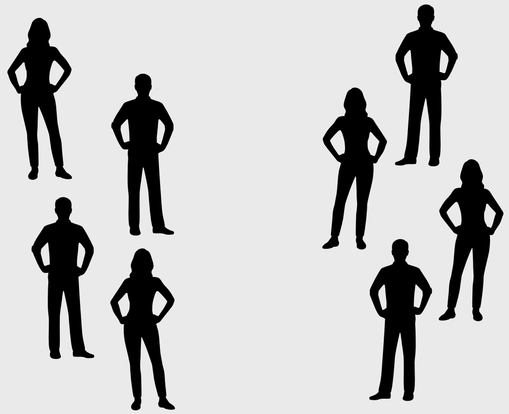
Selection

Q: What's the underlying computation!?

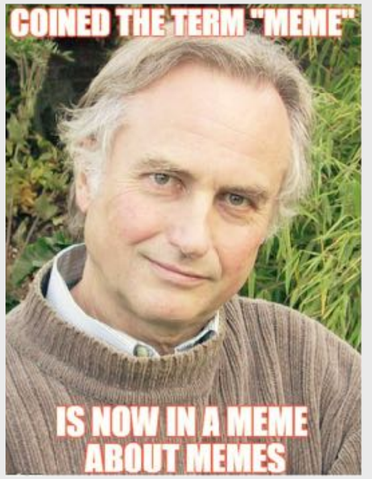
Examples of Evolutionary Thinking

Example 1:
Sexual Dimorphism

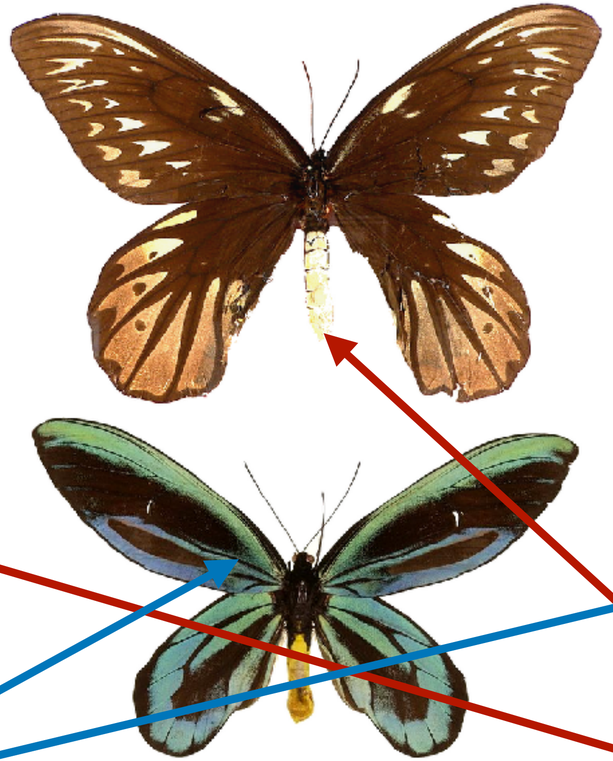
Example 2:
Group Selection

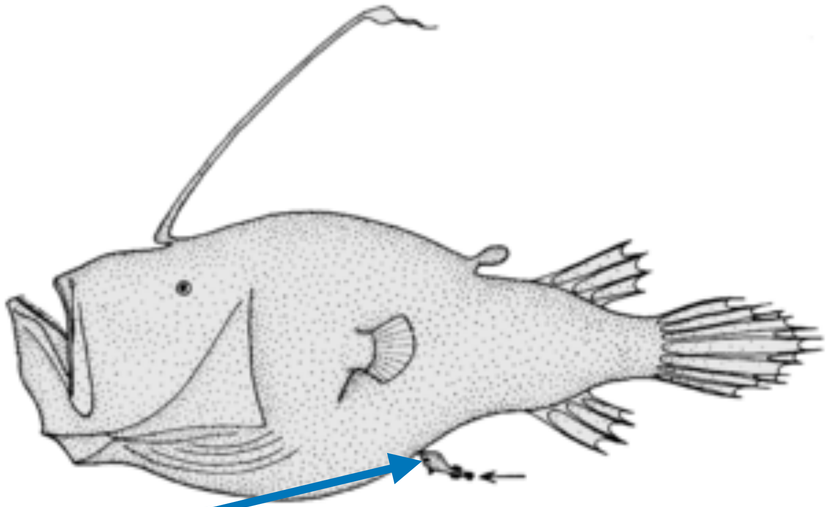


Example 3:
Meme



Example 1: Sexual Dimorphism





Male

Female

Two Types of Sexual Selection

There are other new theories proposed in modern studies!

Intersexual selection

Intrasexual selection

A mixture of these two selection forces?

Example 2: Group Selection

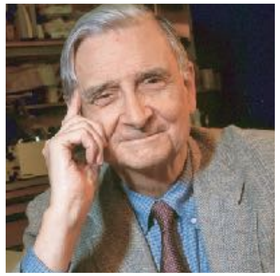
"A tribe a moral men have an immense advantage over a group of fractious bands of pirates!?"

THE

DESCENT OF MAN,

Intuitively, this seems to make sense, but how to scientifically argue it? Difficulties are:

- Selection happens in multilevel.
- Selection forces at different levels might contradict to each other.



E. O. Wilson
1921-2021

"In a group, selfish individuals beat altruistic individuals. But, groups of altruistic individuals beat groups of selfish individuals."

– E. O. Wilson

* This is a relatively controversial topic and here I just present what have been studied and proposed and leave the interpretation to you.

The Foundress's Dilemma

Both types of queen exist!
Why!?

Aggressive

Cooperative

Lower colony density

Higher colony density

In other cases of group selection, there could be more complicated structure of selection forces!

* Shaffer, Zachary, et al. "The foundress's dilemma: group selection for cooperation among queens of the harvester ant, Pogonomyrmex californicus." *Scientific Reports* 6.1 (2016): 1-9.

Example 3: Meme

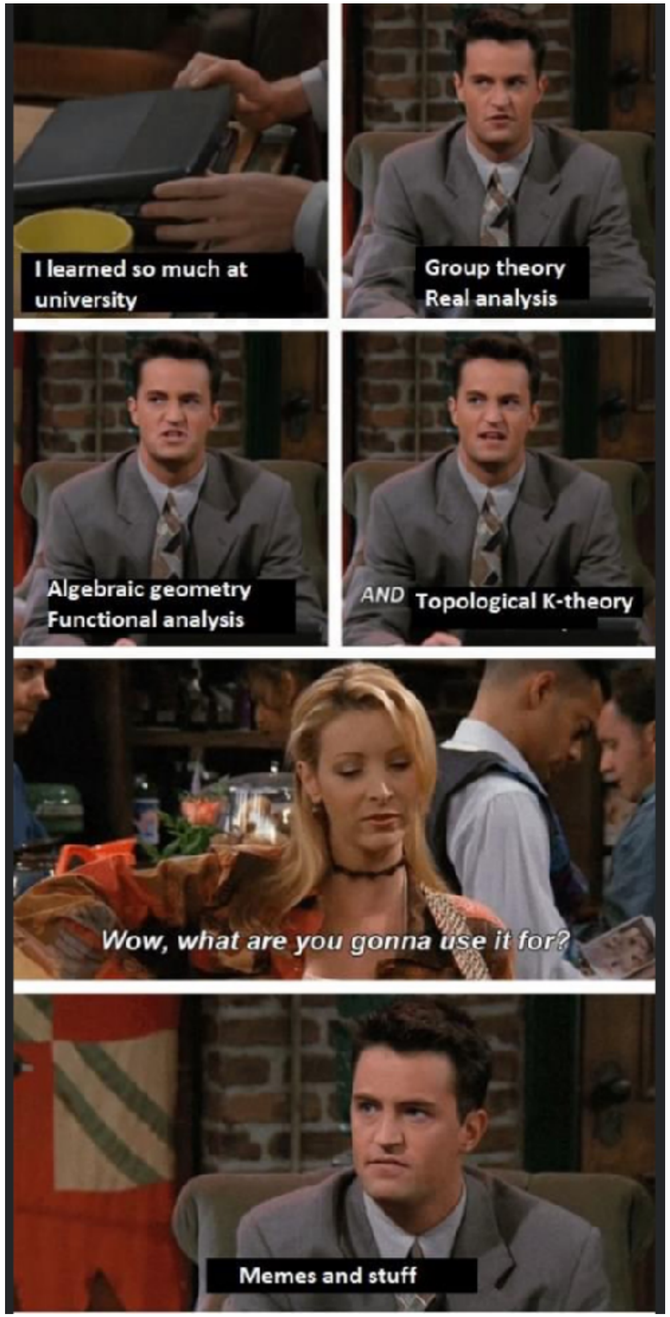
Richard Dawkins
1941-present

"We need a name for the new replicator, a noun that conveys the idea of a unit of cultural transmission, or a unit or imitation."

– Richard Dawkins

More than the memes on the internet…

Politics **Religion** **Science** **…**



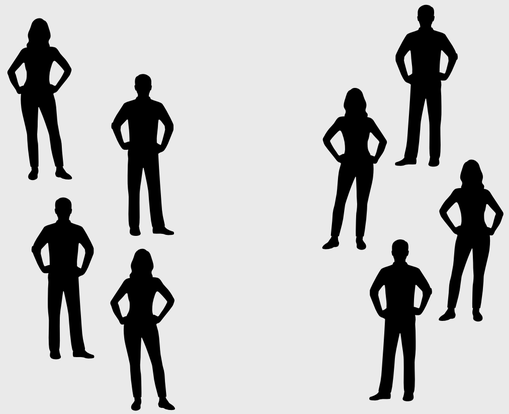
* The meme was suggested by Juspreet Singh Sandhu.

Examples of Evolutionary Thinking

Example 1:
Sexual Dimorphism

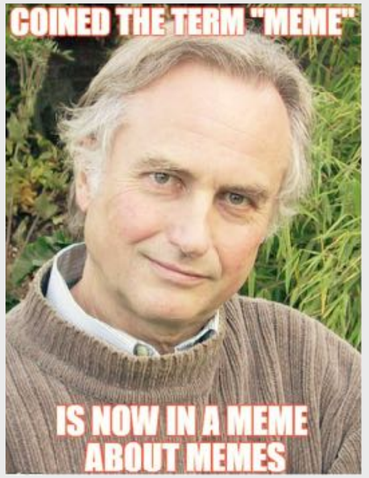
Multiple
selection forces

Example 2:
Group Selection



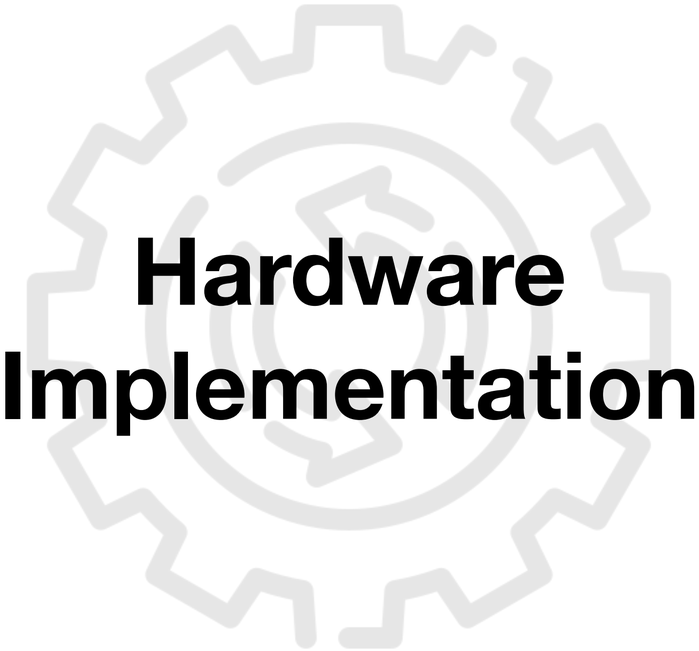
Multiple
levels of selection

Example 3:
Meme



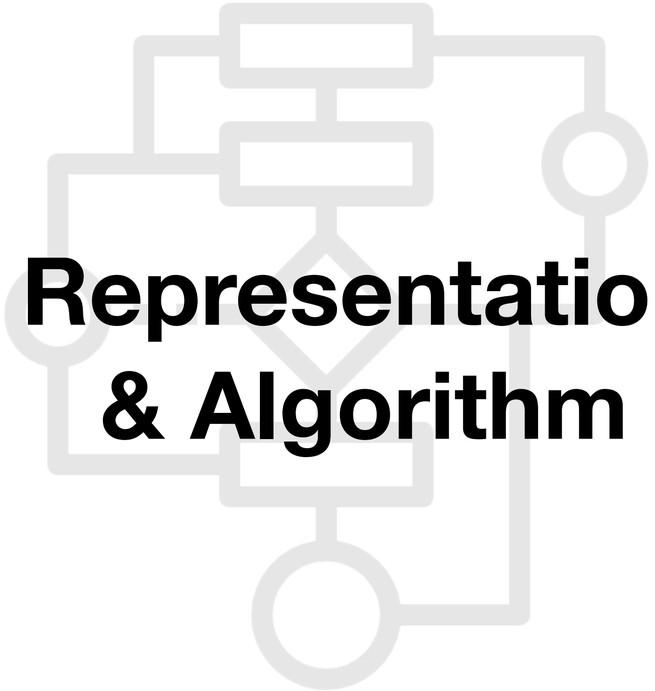
Selection in
human culture

Evolution as a Computational Principle



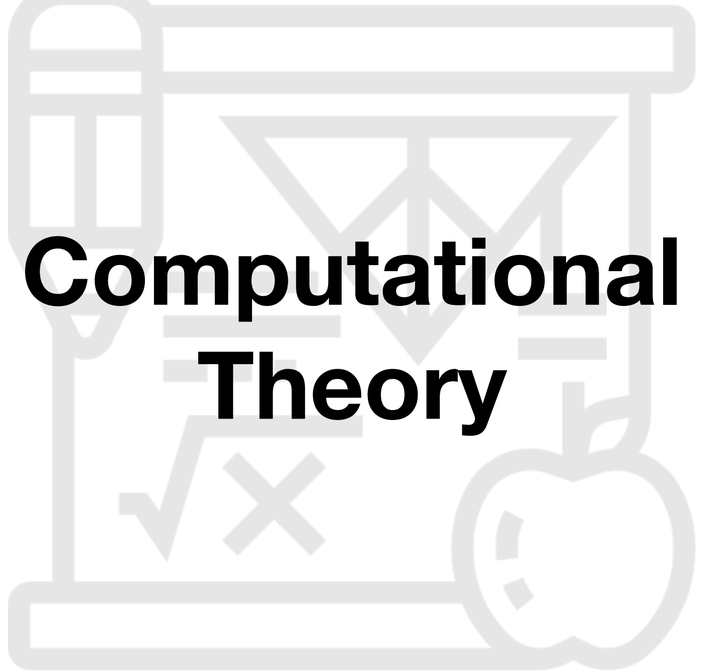
Hardware Implementation

E.g., gene and fossils



Representation & Algorithm

E.g., mechanism for sexual dimorphism, meme



Computational Theory

E.g., natural selection

Common Misunderstanding

Q: Evolution as an optimization (i.e., optimizing the fitness)!?

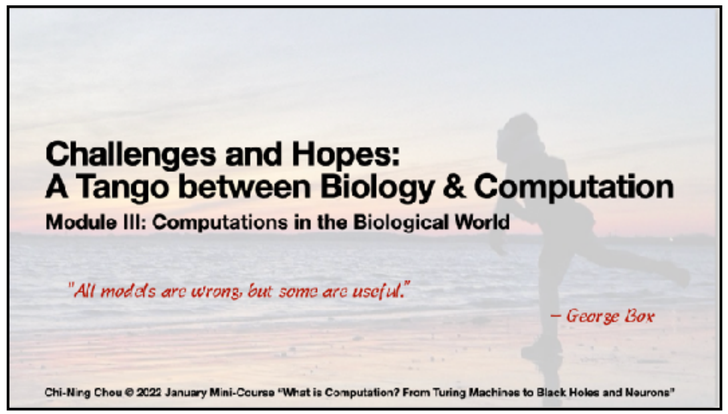
A: Not really!

"Evolution has no long-term goal.

There is no long-distance target,

no final perfection to serve as a criterion for selection."

– Richard Dawkins



Lecture III.c

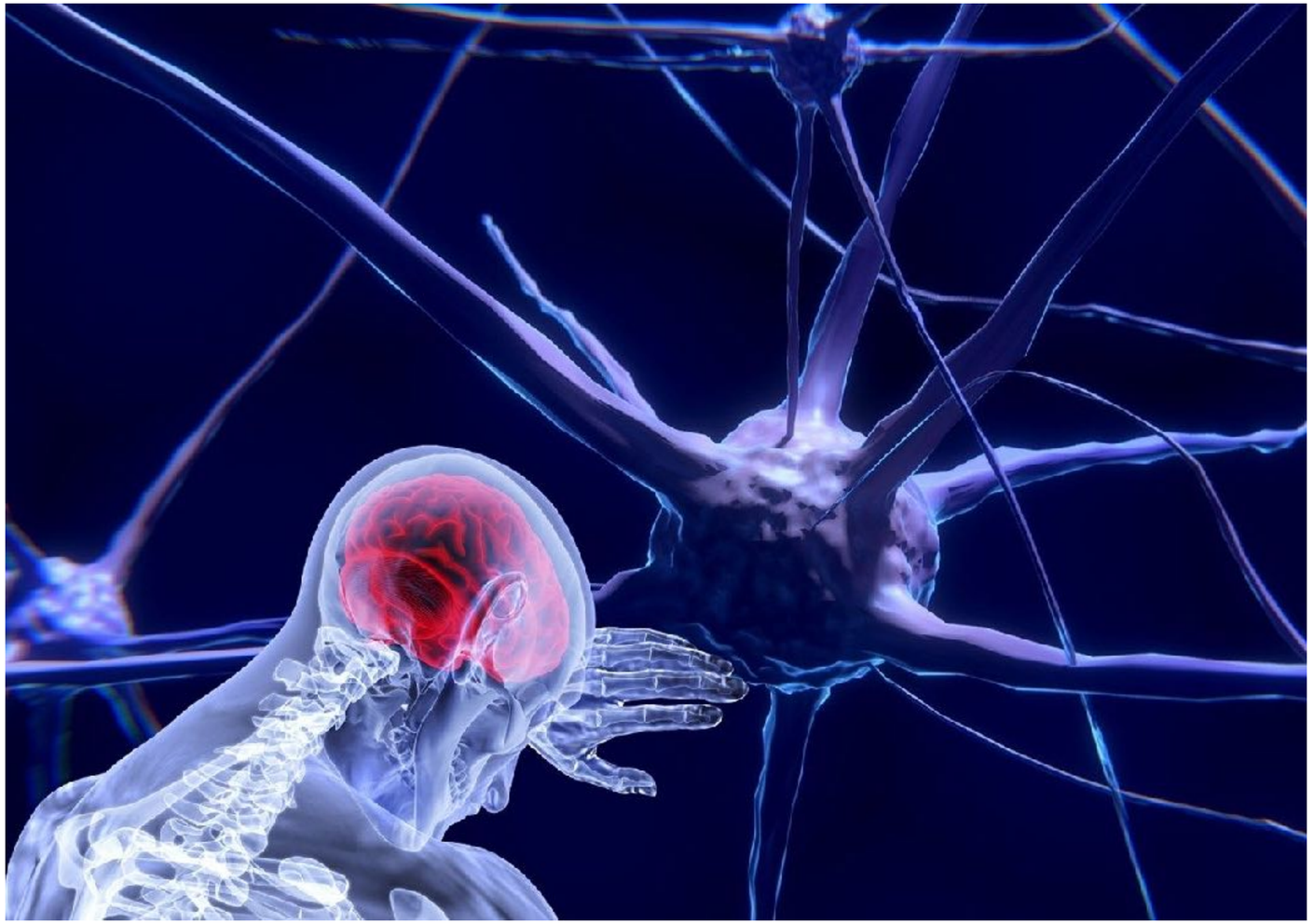
(Jan. 20 10am-10:50am ET)

Neuroscience

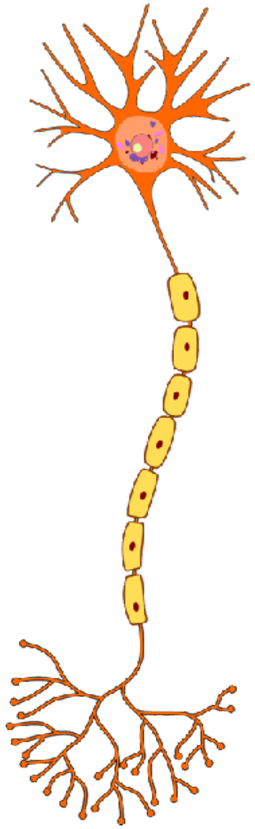
"There is no scientific study more vital to man than the study of his own brain. Our entire view of the universe depends on it."

– Francis Crick

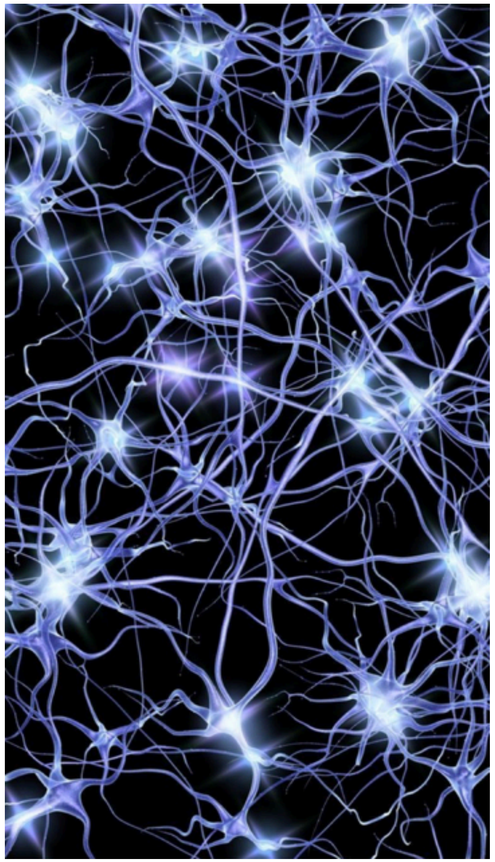
The Biggest Mystery



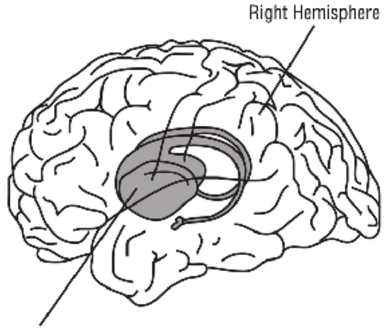
From Neuron to Consciousness

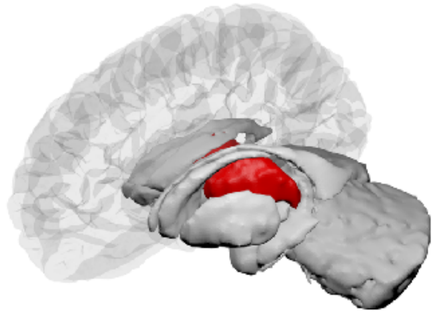


Single neuron



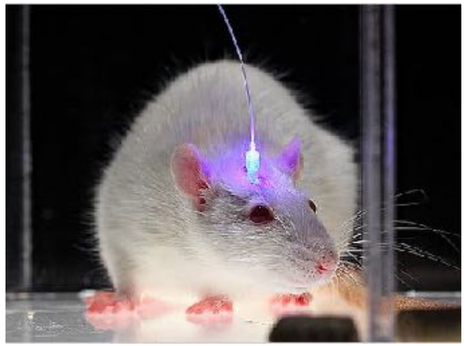
Network





System

Consciousness



Behavior

Many Different Approaches in Neuroscience

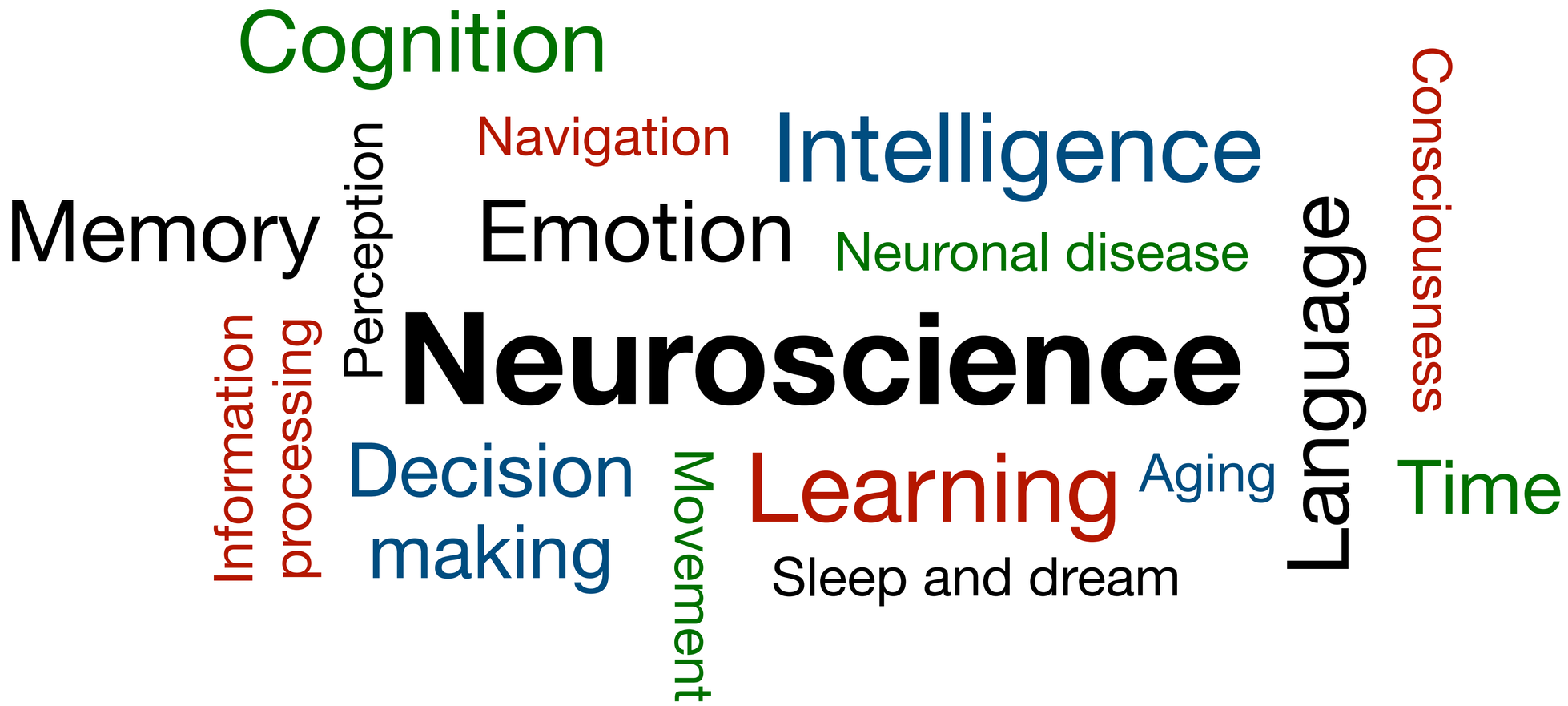
"Our researchers often cross the boundaries of established fields, or invent new disciplines entirely. Conceptually, however, we think of our research in four broad categories:"

– MIT Department of Brain and Cognitive Sciences

- Cellular and Molecular Neuroscience 
- Systems Neuroscience 
- Cognitive Science 
- Computational Neuroscience 

* https://bcs.mit.edu/areas-research

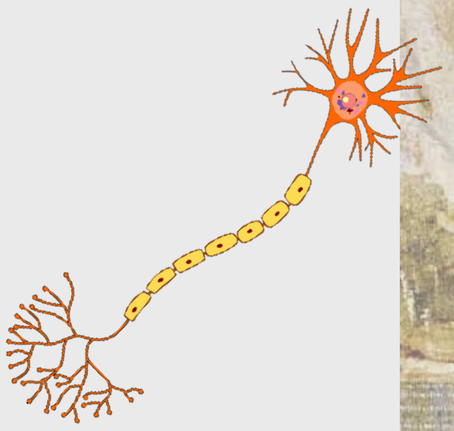
Computations in the Brain?



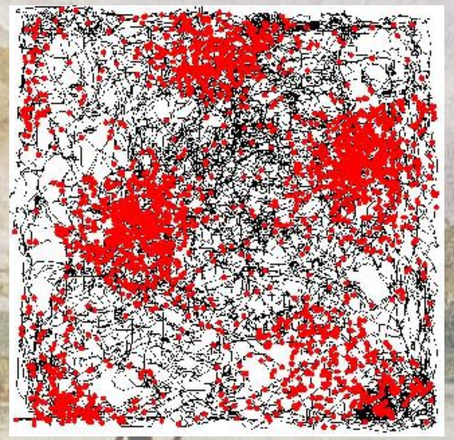
So many aspects mingle together, how do we start!?

Beagle Expedition in Neuroscience!?

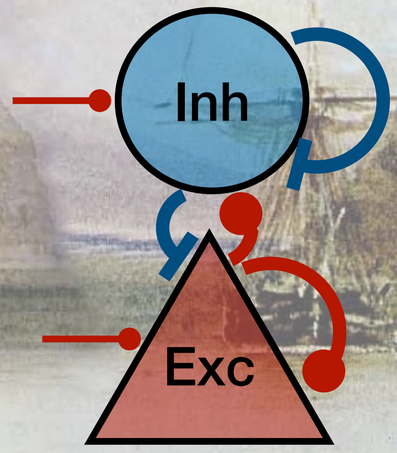
Example 1:
Single Neuron



Example 2:
Grid Cells



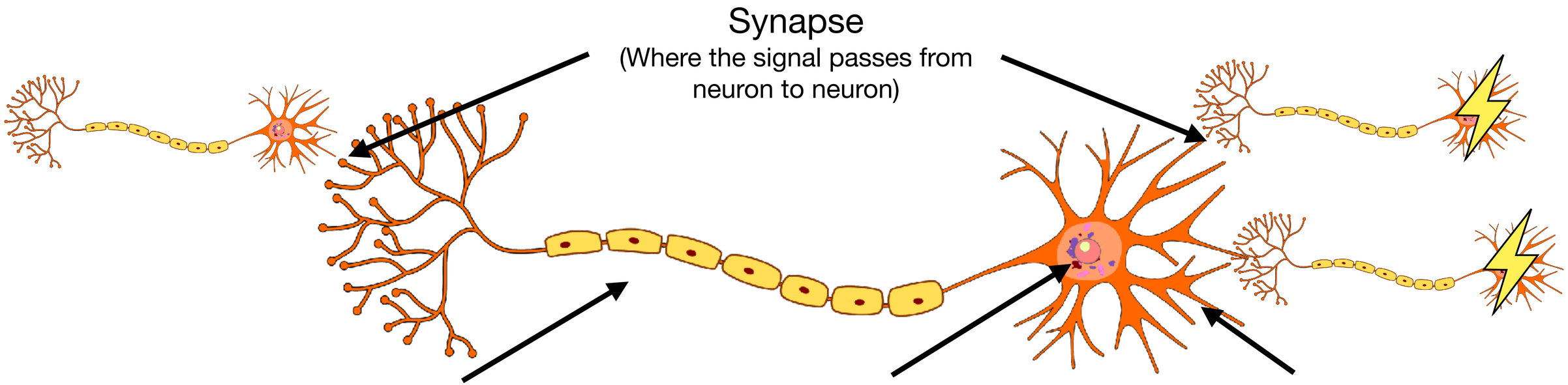
Example 3:
Inhibition Stabilized Networks



More!

Brabeeba Wang
(Jan. 20 11am-12pm ET)

Example 1: Single Neuron

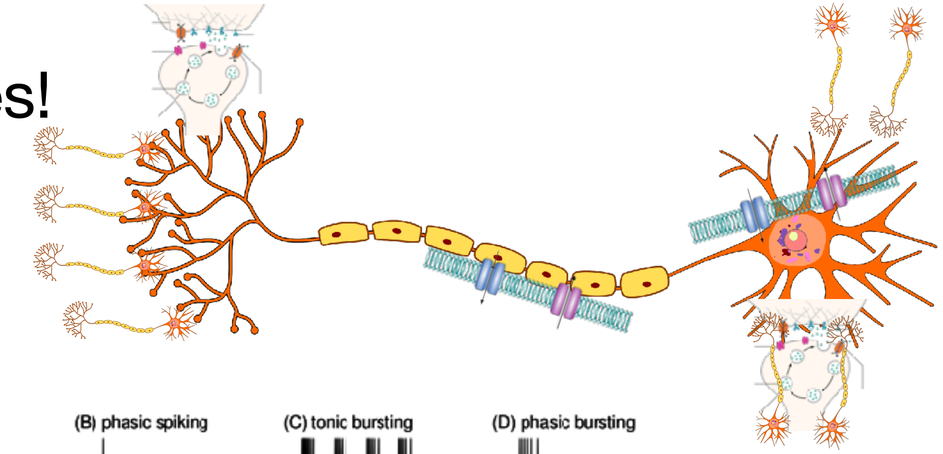


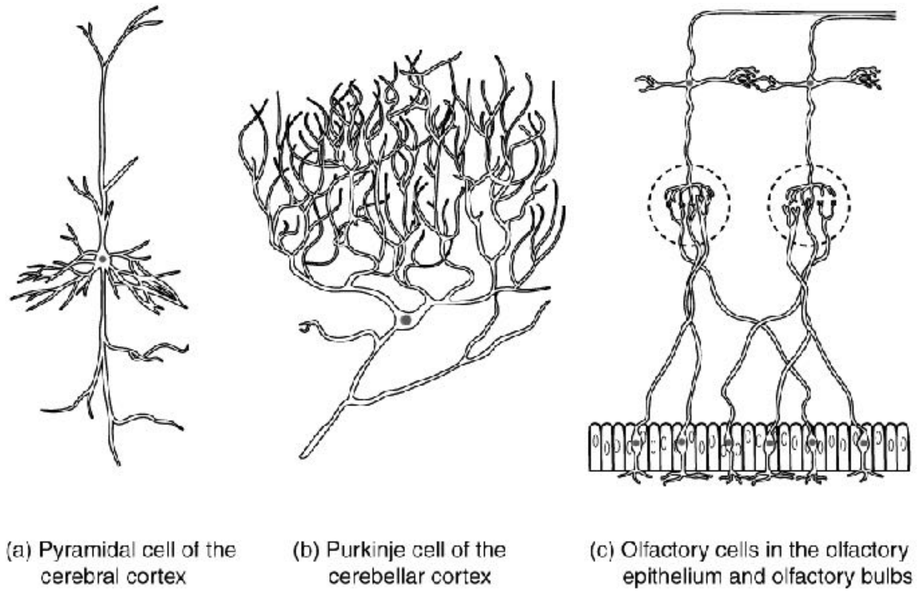
This is oversimplified, in real brain there are special cases and are ubiquitous!

Neurons Can be Complicated and Diverse

There are many factors decide neuron's activities!

- Ion channel (interaction with the outside environment).
- Neurotransmitter (interaction with other neurons).
- Axon and dendrite (geometry of the interconnection).
- …

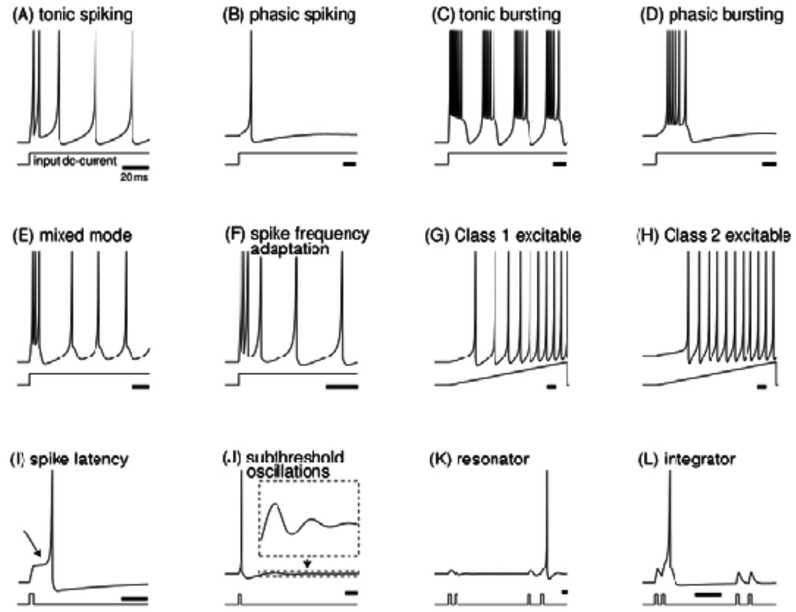




(a) Pyramidal cell of the cerebral cortex

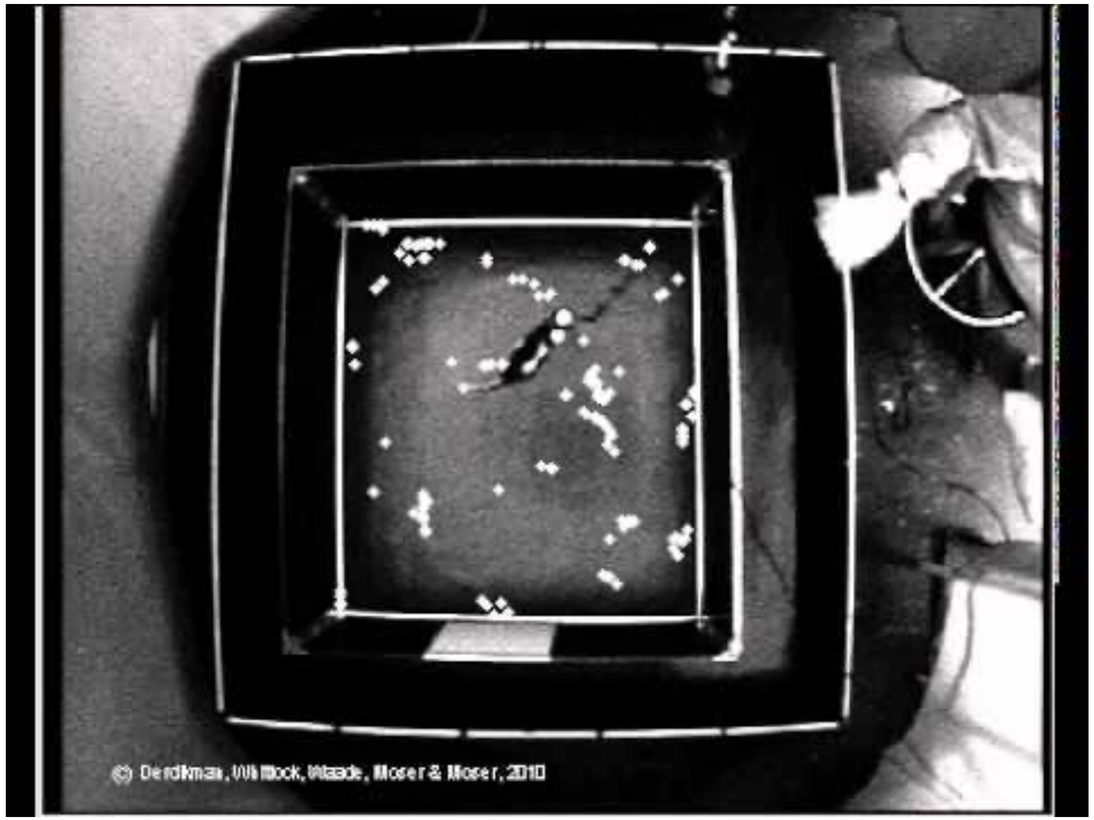
(b) Purkinje cell of the cerebellar cortex

(c) Olfactory cells in the olfactory epithelium and olfactory bulbs

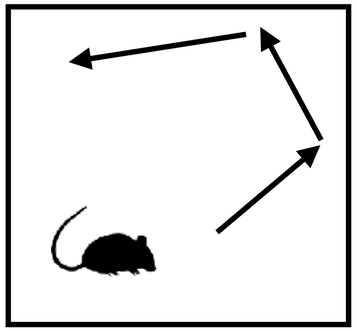


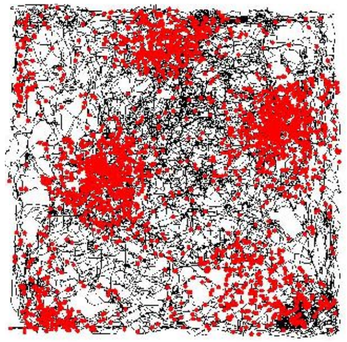
Single neuron seems to do lots of computation already!?

Example 2: Grid Cells



The 2014 Nobel Prize in Physiology or Medicine

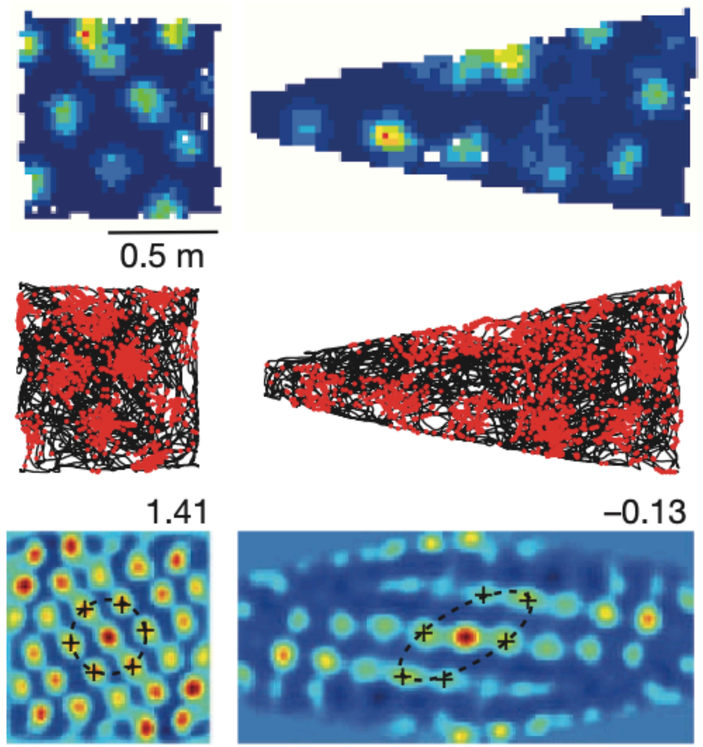




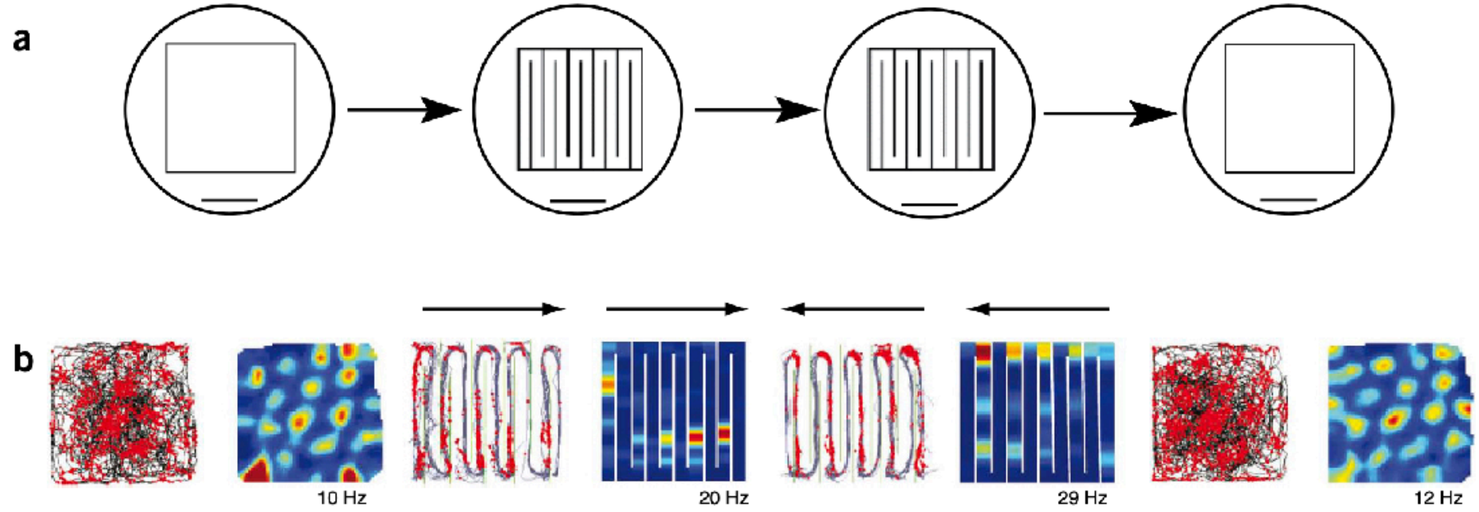
Receptive field of a single grid cell

This is oversimplified, in real mice there are many special cases!

Not Always Hexagonal Grids!



* Krupic, Julija, et al. "Grid cell symmetry is shaped by environmental geometry." *Nature* 518.7538 (2015): 232-235.



* Derdikman, Dori, et al. "Fragmentation of grid cell maps in a multicompartment environment." *Nature neuroscience* 12.10 (2009): 1325-1332.

Q: Why and how grid cells emerge?

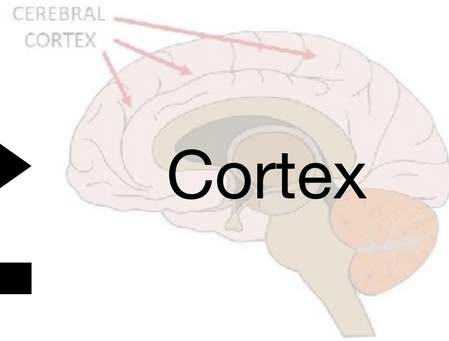
Q: What computation are grid cells doing?

Q: What's the role of grid cells in the brain?

Example 3: Inhibition Stabilized Networks

Toward understanding cortical computation

(Sensory) Input → Thalamus ⇄ Cortex ↻

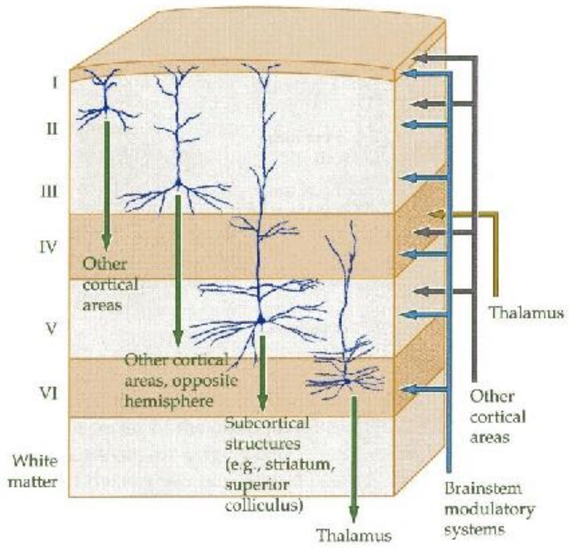


Cortex plays a key role in lots of aspects of computation!

Q: How does cortex reconcile the feedforward and recurrent interactions?

Meanwhile, cortex is very structured!

Q: Network motifs and cortical sub-functions?

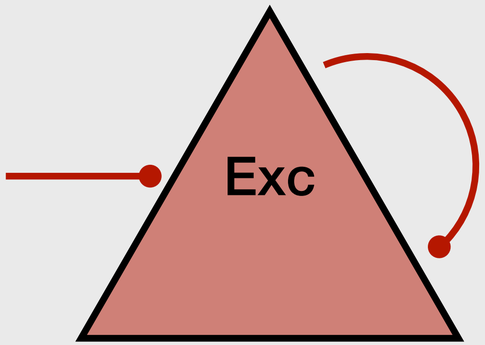


Excitatory

Inhibitory

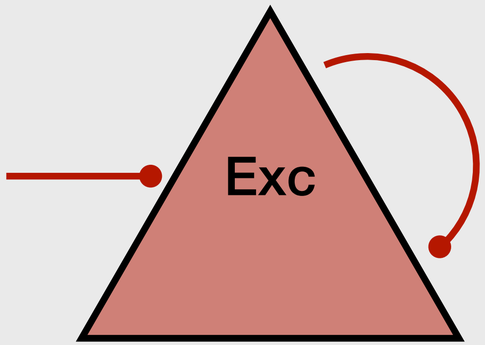
Network Motifs Prosed by Theory

Selecting Patterns



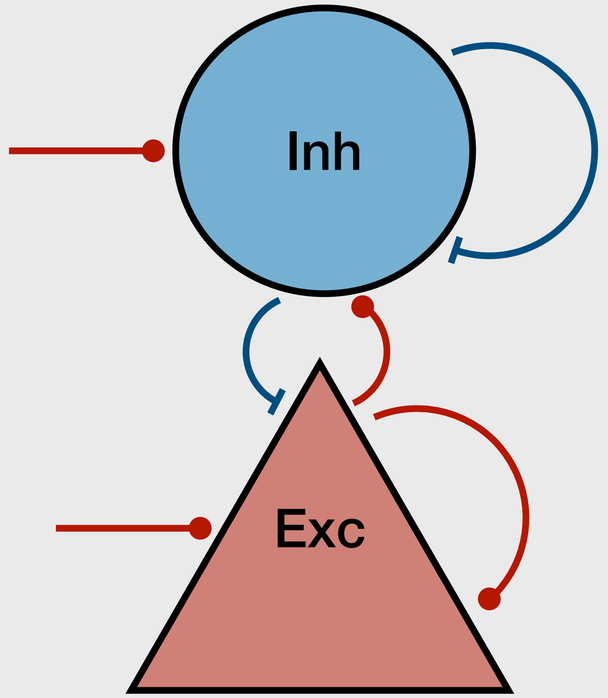
Strong excitatory recurrence constraints the set of stable activity patterns.

Amplifying Inputs



Strong excitatory recurrence amplifies the feedforward inputs (e.g., from thalamus).

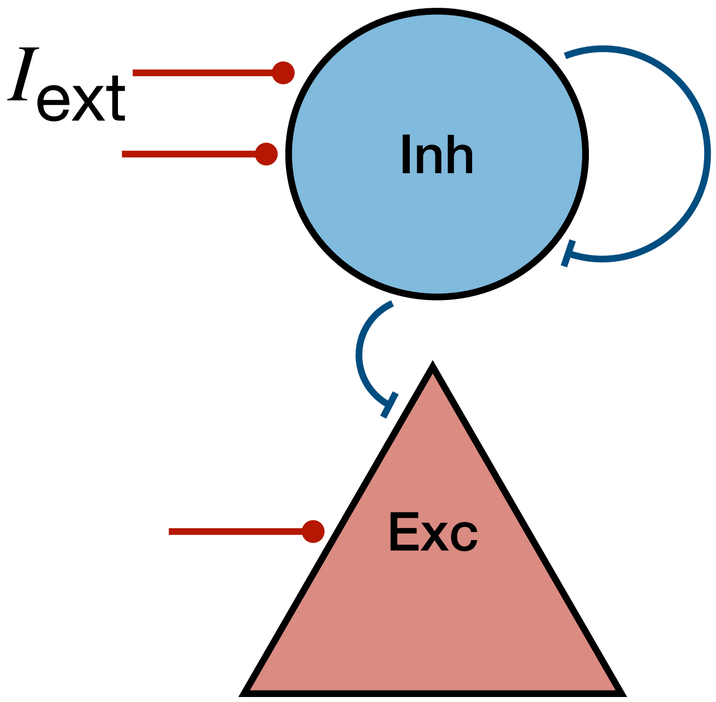
E/I Balance Network



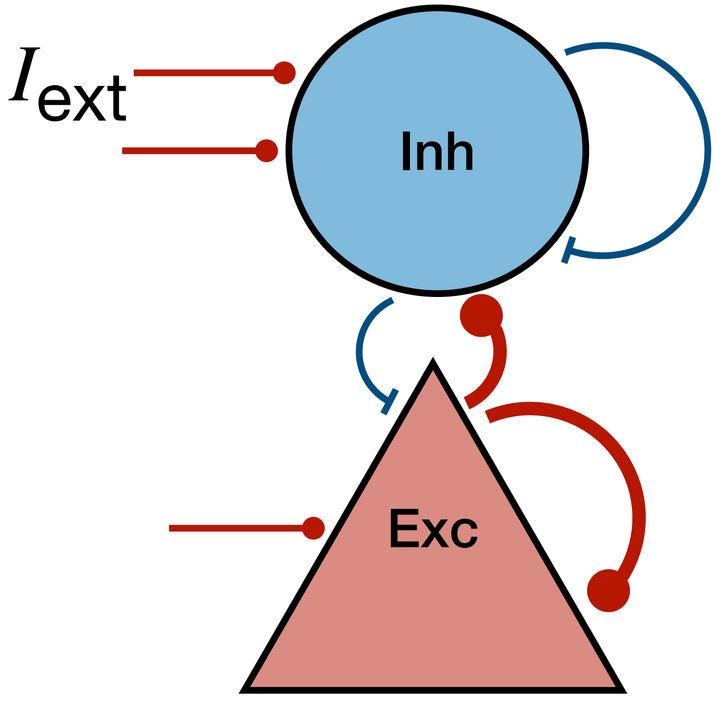
Variability of cortical spiking.

Connectivity Strengths Matter!

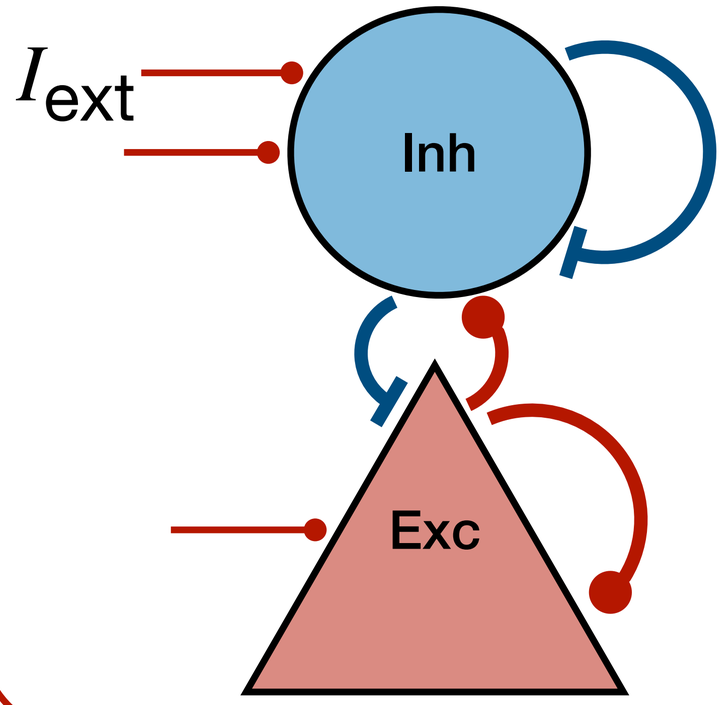
Feedforward Inhibition



Recurrent Inhibition



Inhibition-Stabilized

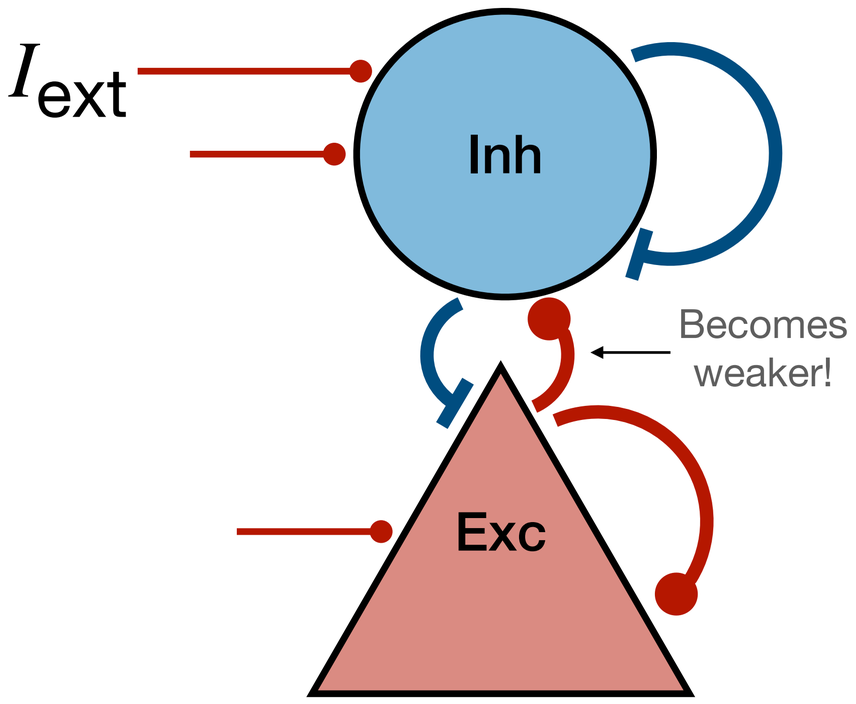


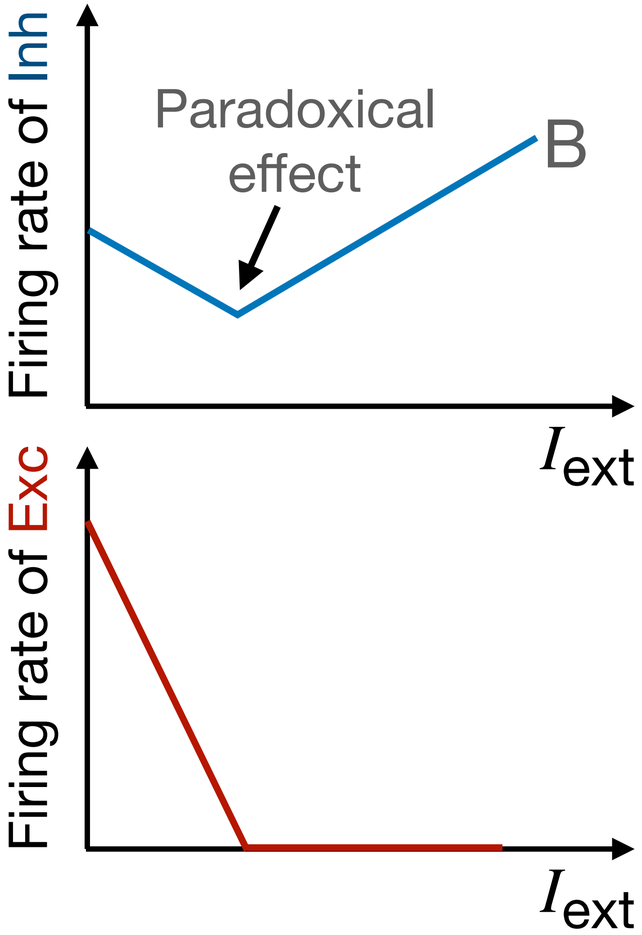
Different connectivity strengths induces different activity patterns!

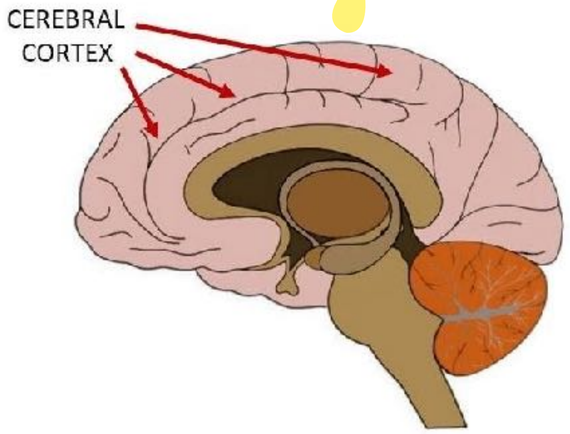
Paradoxical Effect

An interesting activity pattern in inhibition-stabilized networks(ISNs)

Experimentally observed!







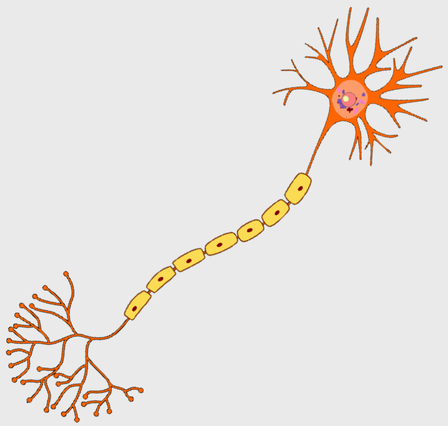
Key: The recurrent excitation was too strong when $I_{\text{ext}} = 0$!

Q: What's the role of these motifs?

Q: How computation happen in cortex?

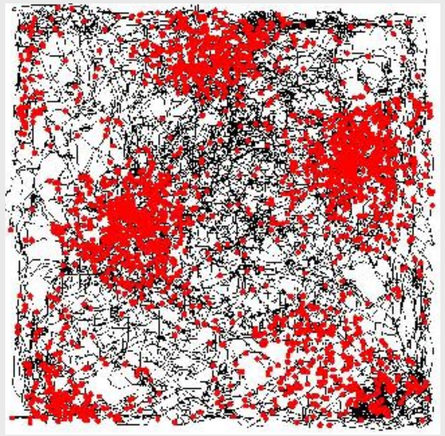
Beagle Expedition in Neuroscience!?

Example 1:
Single Neuron



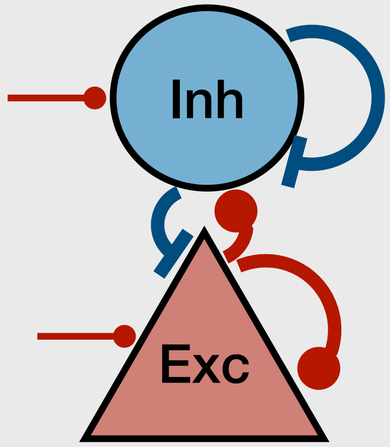
Lowest level

Example 2:
Grid Cells



Near the middle of the brain

Example 3:
Inhibition Stabilized Networks



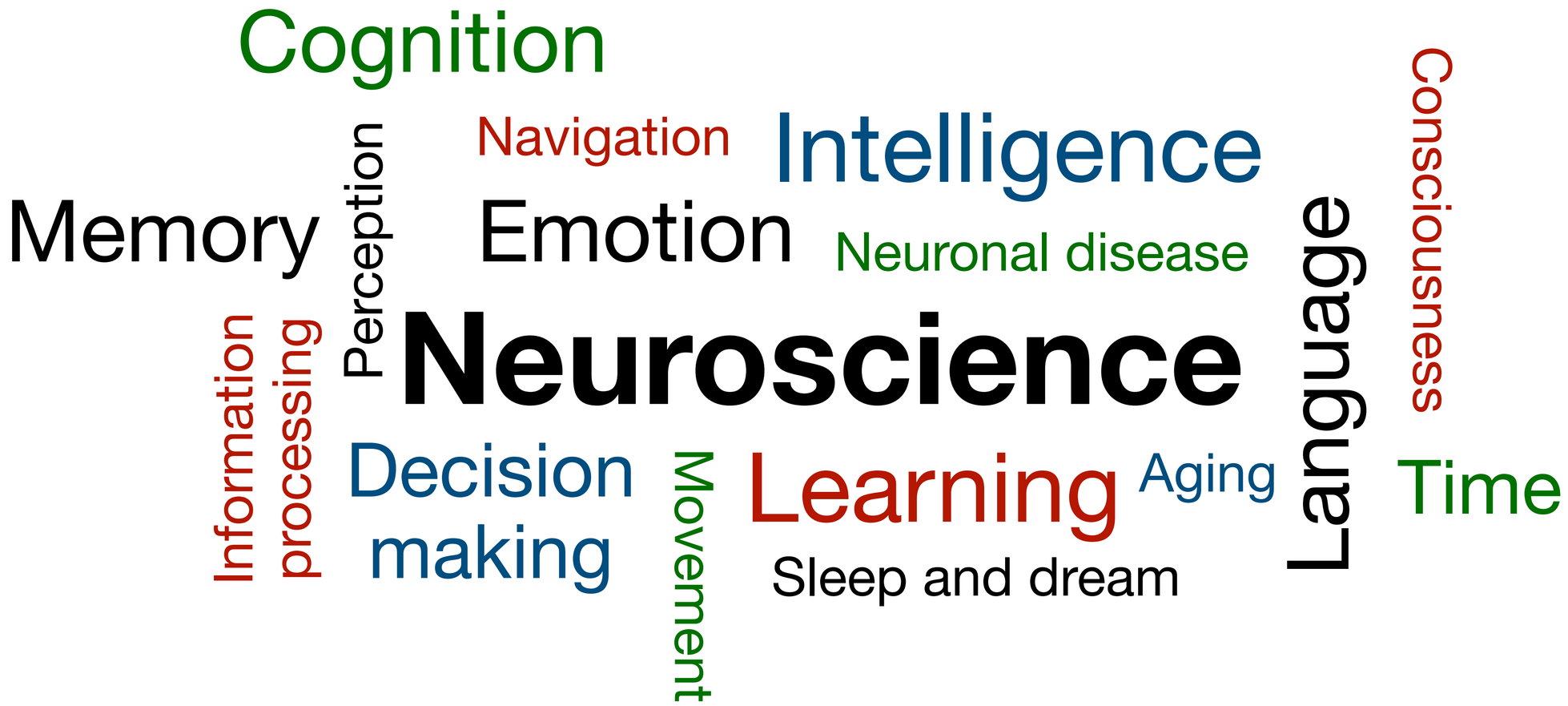
An abstract model

More!

Brabeeba Wang
(Jan. 20 11am-12pm ET)

Flexible decision making in mice

How Do All the Aspects Harmonize?



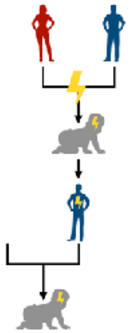
The lack of identifying right computational principles?

Summary

Key Concepts

The Essence of Natural Selection

Common descent



Heredity & Variation

Competition & Fitness

Examples of Evolutionary Thinking

Example 1:
Sexual Dimorphism

Multiple
selection forces

Example 2:
Group Selection

Multiple levels of
selection

Example 3:
Meme

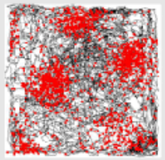
Selection in
human culture

Beagle Expedition in Neuroscience!?

Example 1:
Single Neuron

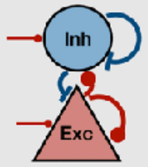
Lowest level

Example 2:
Grid Cells



Near the middle
of the brain

Example 3:
Inhibition Stabilized
Networks



An abstract model

More!

Brabeeba Wang
(Jan. 20 11am-12pm ET)

Flexible decision
making in mice

How Do All the Aspects Harmonize?

Cognition
Memory
Perception
Navigation
Intelligence
Emotion
Neuronal disease
Consciousness
Information processing
Neuroscience
Language
Decision making
Movement
Learning
Aging
Time
Sleep and dream

The lack of identifying right computational principles?

Guest Speakers for Module III

Angel Hsing-Chi Hwang
(Jan. 17 11am-12pm ET)

"Into the Unknown: (De)constructing Creativity in the Age of Human-Machine Partnership"

"A Road to Totality: Between Art and Computation"

Zhiqian Wang
(Jan. 19 11am-12pm ET)

Brabeeba Wang
(Jan. 20 11am-12pm ET)

"Animal Intelligence: Flexible Computation Under Uncertainty"

Next

Lecture III.c

(Jan. 20 10am-10:50am ET)

Salvador

(Jan. 19
2pm-3pm ET)

"DNA Computing, Cellular Automata, and Beyond"

Simone

(Jan. 14
2pm-3pm ET)

"Simulated Annealing"

Check them out on the calendar!

References

Articles:

- Schnitzer, M. Biological computation: Amazing algorithms. Nature 416, 683 (2002), link.
- Chelly Dagdia, Z., Avdeyev, P. & Bayzid, M.S. Biological computation and computational biology: survey, challenges, and discussion. Artif Intell Rev 54, 4169–4235 (2021), link.

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- Jones, Neil C., Pavel A. Pevzner, and Pavel Pevzner. An introduction to bioinformatics algorithms. MIT press, 2004, link.
- Gillespie, John H. Population genetics: a concise guide. JHU Press, 2004, link.

Fun reads:

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- Banatre, Jean-Pierre, et al., eds. Unconventional Programming Paradigms: International Workshop UPP 2004, Le Mont Saint Michel, France, September 15-17, 2004, Revised Selected and Invited Papers. Vol. 3566. Springer Science & Business Media, 2005, link.